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Effects of temperature and humidity on the daily new cases and new deaths of COVID-19 in 166 countries

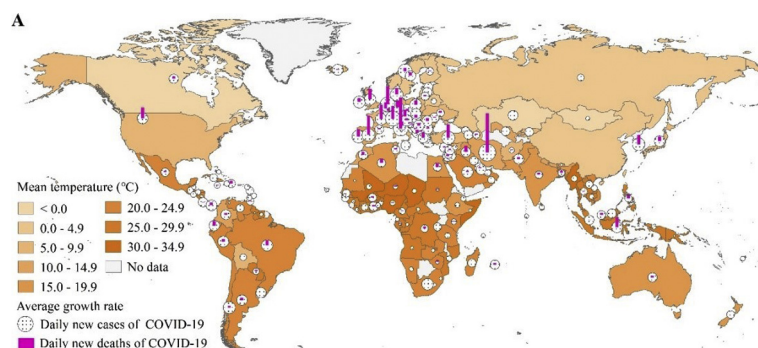
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HIGHLIGHTS

- First study to explore the effects of temperature and humidity on the daily new cases and deaths of COVID-19 worldwide.
- We used log-linear GAM to analyze the effects.
- We considered the lag effects and the cumulative effects of weather conditions.
- Temperature and relative humidity were both negatively related to the daily new cases and daily new deaths of COVID-19

GRAPHICAL ABSTRACT



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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic is the defining global health crisis of our time and the greatest challenge facing the world. Meteorological parameters are reportedly crucial factors affecting respiratory infectious disease epidemics; however, the effect of meteorological parameters on COVID-19 remains controversial. This study investigated the effects of temperature and relative humidity on daily new cases and daily new deaths of COVID-19, which has useful implications for policymakers and the public. Daily data on meteorological conditions, new cases and new deaths of COVID-19 were collected for 166 countries (excluding China) as of March 27, 2020. Log-linear generalized additive model was used to analyze the effects of temperature and relative humidity on daily new cases and daily new deaths of COVID-19, with potential confounders controlled for, including wind speed, median age of the national population, Global Health Security Index, Human Development Index and population density. Our findings revealed that temperature and relative humidity were both negatively related to daily new cases and deaths. A 1 °C increase in temperature was associated with a 3.08% (95% CI: 1.53%, 4.63%) reduction in daily new cases and a 1.19% (95% CI: 0.44%, 1.95%) reduction in daily new deaths, whereas a 1% increase in relative humidity was associated with a 0.85% (95% CI: 0.51%, 1.19%) reduction in daily new cases and a 0.51% (95% CI: 0.34%, 0.67%) reduction in daily new deaths. The results remained robust when different lag structures and the sensitivity analysis were used. These findings provide preliminary evidence that the COVID-19 pandemic may be partially suppressed with temperature and humidity increases. However, active measures must be taken to control the source of infection, block transmission and prevent further spread of COVID-19.

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1. Introduction

In December 2019, several cases of a novel coronavirus disease (COVID-19) were reported in Wuhan, China (Guan et al., 2020), which is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Gorbalenya et al., 2020). The majority of individuals with coronavirus experience mild to moderate respiratory illness and recover without specific treatment (World Health Organization, 2020a). However, the elderly and people with underlying medical problems are at a higher risk of severe prognosis (World Health Organization, 2020a; National Health Commission and State Administration of Traditional Chinese Medicine, 2020). A model-based analysis estimated that the case fatality ratio in China was 1.38%, and up to 13.4% in individuals aged 80 years or older (Verity et al., 2020). On March 11, 2020, the World Health Organization (WHO) categorized COVID-19 as a pandemic, because the number of cases increased drastically outside China (World Health Organization, 2020b). As of April 10, 2020, there have been almost 1.5 million confirmed cases in 184 countries/regions, and over 92,000 deaths worldwide (World Health Organization, 2020c; Johns Hopkins University, 2020).

Research has reported that seasonal cyclicality is a ubiquitous feature of acute infectious diseases, which is also commonly observed in respiratory viral diseases (Martinez, 2018). For instance, influenza outbreaks occur every winter in temperate regions (Shaman et al., 2010). An epidemiological model in the United States indicated that absolute humidity affected the seasonality of influenza incidence (Shaman et al., 2010). Moreover, severe acute respiratory syndrome (SARS) broke out in China in mid-November 2002, and had almost entirely resolved by July 2003 (Tan et al., 2005; Ma et al., 2020). A study in China that was based on case studies in Hong Kong, Guangzhou, Beijing, and Taiyuan indicated that the outbreaks of SARS were significantly associated with variations in temperature (Tan et al., 2005).

Emerging laboratory and epidemiological data suggest that environmental conditions may affect the current COVID-19 pandemic (Jon Brassey et al., 2020). A published laboratory study by Chin et al. (2020) reported that SARS-CoV-2 was highly stable at 4 °C but sensitive to heat. The virus survival time was shortened to 5 min as the incubation temperature increased to 70 °C. Epidemiological studies have explored the relationship between COVID-19 and meteorological parameters; however, findings are controversial (Ma et al., 2020; Xie and Zhu, 2020; Yao et al., 2020). A study by Xie and Zhu (2020) reported that a 1 °C rise was associated with a 4.861% increase in the daily confirmed cases of COVID-19, when mean temperature (lag 0–14) was below 3 °C. A study by Ma et al. (2020) reported a positive association between daily deaths of COVID-19 and diurnal temperature range, and a negative association for relative humidity. However, a study by Yao et al. (2020) reported that COVID-19 transmission did not exhibit an association with temperature in Chinese cities.

COVID-19 continues to spread globally, and a second wave of COVID-19 appears probable (Leung et al., 2020; Price et al. 2019) thus, the effect of meteorological parameters on the spread of COVID-19 should be explored to help predict the development over the coming months, although numerous factors may affect the progression of the COVID-19 pandemic. Therefore, this study explored the effects of temperature and humidity on the daily new cases and deaths of COVID-19 in 166 countries using a generalized additive model (GAM), to provide useful implications for policymakers and the public.

2. Methods

2.1. Data collection

Data of COVID-19 cases were collected in 166 countries (excluding China) as of March 27, 2020 for analysis. Data, including daily new cases and daily new deaths, were collected from the WHO daily

COVID-19 situation reports (<https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports>).

The monitoring stations nearest to each country's capital were used. Daily meteorological data, including daily average temperature, average dew point, and average wind speed, were obtained from the National Oceanic and Atmospheric Administration Center (<https://www.ncei.noaa.gov/access/search/data-search/global-summary-of-the-day>).

2.2. Calculation of relative humidity

Relative humidity is the ratio of the actual water vapor pressure to the saturation water vapor pressure at the prevailing temperature, calculated using the following equation:

$$\text{Relative humidity} = \frac{E}{E_w} \times 100\%$$

where E (hPa) denotes the vapor pressure of air at temperature t (°C). E_w (hPa) denotes the saturated vapor pressure of the pure horizontal liquid surface at dry bulb temperature t (°C). The dew point is the temperature at which air must be cooled to become saturated with water vapor. The actual vapor pressure E can be calculated using the dew point temperature and the saturated vapor pressure can be calculated from the actual temperature using the Magnus formula for saturation water vapor pressure (Chen, 1997; Steven et al., 2020):

$$E = E_0 \times e^{\frac{At}{B+t}}$$

where E_0 denotes saturation vapor pressure at a reference temperature T_0 (273.15 K) which equals 6.11 mb. A is a constant of 17.43 and B is a constant of 240.73. t (°C) is the actual temperature or dew point.

2.3. Control variables

Five variables were included in the model as potential confounders: wind speed (<https://www.ncei.noaa.gov/access/search/data-search/global-summary-of-the-day>), median age of the national population (<https://ourworldindata.org/age-structure2019>), Global Health Security Index (GHSI, <https://www.ghsindex.org/wp-content/uploads/2020/04/2019-Global-Health-Security-Index.pdf>), Human Development Index (HDI, <http://hdr.undp.org/sites/default/files/hdr2019.pdf>) and population density (<https://worldpopulationreview.com/countries/countries-by-density/>). Wind is a crucial factor in the transmission of respiratory infectious diseases and it may modulate the dynamics of various vectors and pathogens (Ellwanger and Chies, 2018). Median age of the national population is an indicator of population aging; the incidence of severe cases is higher in countries with higher levels of population aging (Verity et al., 2020). GHSI is the first comprehensive assessment of global health security capabilities to be employed in 195 countries; the 2019 GHSI report scored (out of 100) the country-level capacity for “early detection and reporting for epidemics of potential concern.” HDI is a summary measure of average achievement in three key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. Population density is expressed as the number of people per square mile of land area; a high population density can promote the spread of epidemics (Khairat et al., 2020).

2.4. Statistical methods

In the present study, 166 countries with confirmed cases as of March 27, 2020 were included. Descriptive analyses were performed for all the data. A log-linear GAM was used to analyze the associations between meteorological factors (temperature and relative humidity) and daily new cases and daily new deaths of COVID-19 (Samet et al., 2000).

First, the basic models were constructed, including meteorological factors (temperature and relative humidity). Second, the variables were controlled to adjust for regional variation, including wind speed, median age of the population, GHSI, and country. Third, the day-of-week and the penalized smoothing spline functions were incorporated to control the time trend and cycle. The core GAM equation was as follows:

$$\log(Y_t) = \alpha + \beta X_t + \text{Wind} + \text{Country} + \text{Median.Age} + \text{GHSI} + \text{DOW} + s(\text{Time}, df)$$

where t is the day of the observation. Considering that the number of daily new cases or daily new deaths in some countries is 0, Y_t is the number of daily new cases or daily new deaths on day t plus one. α is the intercept; β is the regression coefficient; X_t is the weather variables on day t ; *Wind* is the wind speed; *Country* is a categorical variable for country; *Median.Age* is the median age of each countries' population; *GHSI* is the Global Health Security Index; *DOW* is a categorical variable indicating the date of the week; $s()$ refers to the smoother, which is based on the penalized smoothing spline; *Time* is the date of the observation; df is the degree of freedom.

The lag effects of weather conditions on daily new cases and daily new deaths of COVID-19 were then considered using single lag days (lag 0, 1, 2, 3). The cumulative effects of average exposure over multiple days were then assessed using additional analyses (lag 01, 02, 03) to control for the possible misalignment of a single lag day exposure.

All analyses were performed using R software (version 3.6.0) with the “mgcv” package (version 1.8–28). The results were expressed as percentage changes and 95% confidence intervals (CIs) in daily new cases and daily new deaths of COVID-19 associated with a 1 unit increase in weather variables. All tests were two-sided, and a value $P < 0.05$ was considered statistically significant.

2.5. Sensitivity analysis

Two other variables were included in the sensitivity analysis: HDI and population density. Because of the inconsistent outbreak time of COVID-19 in different countries, the transmission mechanism and transmission rate of COVID-19 may differ. Therefore, countries that first reported case relatively early and countries with more cases were selected to fit the core model to determine the stability of results.

3. Results

3.1. Description analysis

A total of 509,164 cumulative confirmed cases and 23,335 deaths had been documented globally as of March 27, 2020. Italy, the United States and Spain were the three countries with the most cases of COVID-19 outside of China. Moreover, Italy, Spain and Iran had the most deaths of COVID-19 outside of China. The average temperatures ranged from -5.28 to 34.30 °C, and the average relative humidity ranged from 11.39% to 88.42% (Fig. 1).

3.2. Effects of temperature and humidity on daily new cases and daily new deaths of COVID-19

After controlling the effects of potential confounders, temperature and relative humidity were both negatively related to the daily new cases and daily new deaths. A 1 °C increase in temperature was associated with a 3.08% (95% CI: 1.53%, 4.63%) reduction in daily new cases and a 1.19% (95% CI: 0.44%, 1.95%) reduction in daily new deaths. A 1% increase in relative humidity was associated with a 0.85% (95% CI: 0.51%, 1.19%) reduction in daily new cases and a 0.51% (95% CI: 0.34%, 0.67%) reduction in daily new deaths. Different lag structures also indicated that temperature and relative humidity were negatively correlated with daily new cases and daily new deaths (Fig. 2). The

strongest cumulative effects were observed at lag 03, with a 1 °C increase in temperature being associated with a 5.94% and 2.30% reduction in daily new cases and daily new deaths, respectively, a 1% increase in relative humidity being associated with a 1.23% and 0.88% reduction in daily new cases and daily new deaths, respectively.

3.3. Sensitivity analysis

Two indicators of HDI and population density were adjusted based on the core model. The results revealed that a 1 °C increase in temperature was associated with a 2.85% reduction in daily new cases and no association with daily new deaths. A 1% increase in relative humidity was associated with a 0.87% reduction in daily new cases and a 0.46% reduction in daily new deaths (Table 1).

The cumulative number of cases and the outbreak time of COVID-19 exhibited a large variation between countries; thus the transmission mode and rate of COVID-19 differ between countries. We selected countries that reported their first case over 10 days before data collection and countries with over 100 cumulative cases to fit the core model. Among countries with over 10 days since the first reported case, a 1 °C increase in temperature was associated with a 3.05% and 1.22% reduction in daily new cases and daily new deaths, respectively, and a 1% increase in relative humidity was associated with a 0.87% and 0.51% reduction in daily new cases and daily new deaths, respectively. In countries with over 100 cumulative cases, a 1 °C increase in temperature was associated with a 2.82% and 1.25% reduction in daily new cases and daily new deaths, respectively; a 1% increase in relative humidity was associated with a 0.86% and 0.53% reduction in daily new cases and daily new deaths, respectively. The results of the comparisons of these datasets with the total data were not significant. These results demonstrate a robust effect of temperature and relative humidity on daily new cases and new deaths of COVID-19 (Table 2).

4. Discussion

The COVID-19 pandemic is the defining global health crisis of our time and the greatest challenge facing the world (United Nations Development Programme, 2020). Our findings revealed that temperature and humidity were inversely correlated with daily new cases and deaths of COVID-19. For every 1 °C increase in temperature, daily new cases of COVID-19 reduced by 3.08% (95% CI: 1.53%, 4.63%) and daily new deaths reduced by 1.19% (95% CI: 0.44%, 1.95%); for every 1% increase in humidity, daily new cases of COVID-19 reduced by 0.85% (95% CI: 0.51%, 1.19%), and daily new deaths reduced by 0.51% (95% CI: 0.34%, 0.67%), according to analyses of 166 countries. After adjusting for potential factors and lag days, the negative relationships remained robust. Furthermore, we hypothesized that the effects of temperature and humidity on daily cases and deaths of COVID-19 may not be evident in countries where the community transmission of COVID-19 had not occurred because the proportion of imported cases was high. Therefore, countries where the time of onset was fewer than 10 days prior, or countries with fewer than 100 cumulative confirmed cases were excluded in the sensitivity analysis. The model-fitting results remained stable.

Few studies have investigated the association of temperature and humidity with COVID-19 incidence and death rates. A preprint study, which investigated the total confirmed cases in 429 cities globally from January 20 to February 4, 2020 indicated that the cumulative number of confirmed cases reduced by 0.86 for every 1 °C increase in the minimum temperature of higher-temperature cities (Wang et al., 2020). Another preprint study by Bannister-Tyrrell et al. (2020) reported that as of February 29, 2020, average temperature increases of 1 °C were negatively correlated with the predicted number of cases worldwide (excluding Hubei Province). Furthermore, a study reported that relative humidity was inversely related to daily deaths of COVID-19 ($r = -0.32$), with the largest reduction in lag 3 [-11.41% (95% CI:

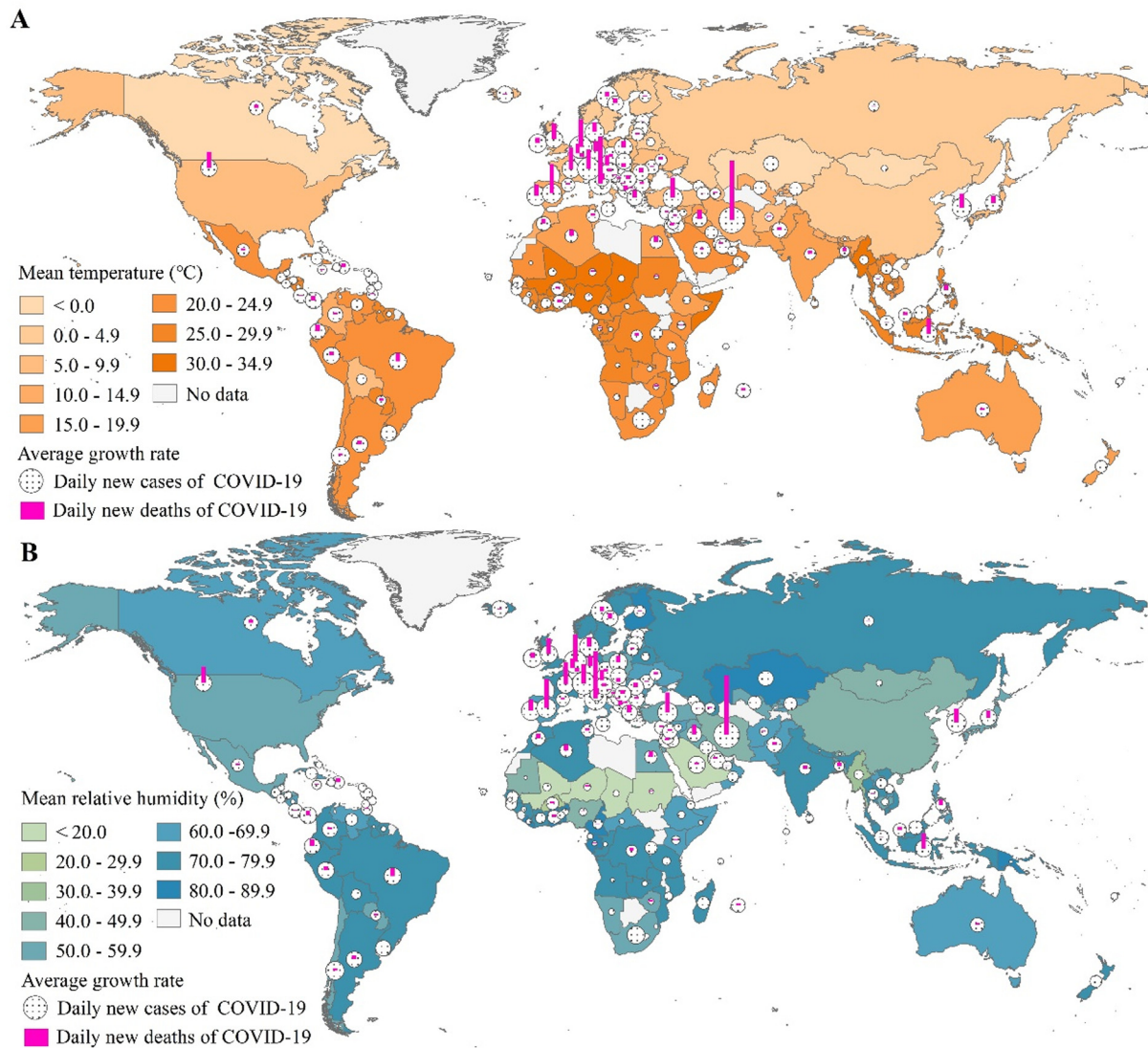


Fig. 1. As of March 27th 2020, distribution of (A) mean temperature and (B) mean relative humidity with the average growth rate of daily new cases and daily new deaths of COVID-19 worldwide. Note: Mean temperature (°C) was the sum of the daily average temperature divided by the number of observed days. Mean relative humidity (%) was the sum of the daily average relative humidity divided by the number of observed days. Average growth rate was the average of the natural logarithm of the number of daily new cases or daily new deaths.

−19.68%, −2.29%)] (Ma et al., 2020). These results accord with our findings.

Other studies have reported conflicting results. A study in 122 cities in China demonstrated that when the mean temperature (lag 0–14) was below 3 °C, the daily confirmed cases of COVID-19 increased by 4.861% (95% CI: 3.209, 6.513%) for every 1 °C rise in temperature (Xie and Zhu, 2020). However, no correlations were observed when the mean temperature was above 3 °C. Another study investigated the daily deaths of COVID-19 in Wuhan, China, from January 20 to February 29, 2020, which revealed that diurnal temperature ranges were positively correlated with daily COVID-19 deaths ($r = 0.44$) (Ma et al., 2020). However, these results were not stable, because the temperature was related to the reduction in COVID-19 deaths in lag 3 [−7.50% (95% CI: −10.99%, −3.88%)] and lag 5. These studies did not report the same trends as our study, which may be because of the different characteristics of the participants and different models. The conflicting study was only conducted in China and the temperature range was limited, whereas our study analyzed several countries.

There are several possible explanations for our findings. Firstly, studies have reported that SARS-CoV-2 is sensitive to high temperature and humidity (Chin et al., 2020; van Doremalen et al., 2020; Chan et al., 2011; Sun et al., 2020; Ma et al., 2020; Wu et al., 2020; Xie and Zhu,

2020; Yao et al., 2020). A laboratory study by Chin et al. (2020) demonstrated a 0.7 log-unit reduction after 14 days of incubation in the virus transport medium at 4 °C (final concentration ~ 6.8 log-unit of 50% tissue culture infectious dose per mL); over 3 log-unit reduction after 7 days of incubation at 22 °C, and no virus detected at 14 days; over 3 log-unit reduction after 1 day of incubation at 37 °C, and no detection afterward. Moreover, a study by van Doremalen et al. (2020) demonstrated that under experimental conditions, the stability of SARS-CoV-2 was similar to that of SARS-CoV. Chan et al. (2011) reported that at temperatures of 22–25 °C and relative humidity of 40%–50%, dried SARS-CoV could survive for over 5 days on smooth surfaces. However, the viability of SARS-CoV reduced rapidly when the temperature or relative humidity increased. Therefore, SARS-CoV-2 may be less stable in high-temperature and high-humidity environments. Second, the moisture in the exhaled bioaerosols evaporates rapidly in low relative humidity, forming droplet nuclei that remain in the air for longer, thereby increasing the likelihood of pathogen transmission (Lowen et al., 2007; Tellier, 2006). Third, the cold weather in winter hinders humans' innate immunity. Cold temperatures cause reduced blood supply and thus reduce the provision of immune cells to the nasal mucosa (Sun et al., 2020). Moreover, low humidity reduces the airway cilia cells' ability to remove virus particles, secrete mucus, and repair airway

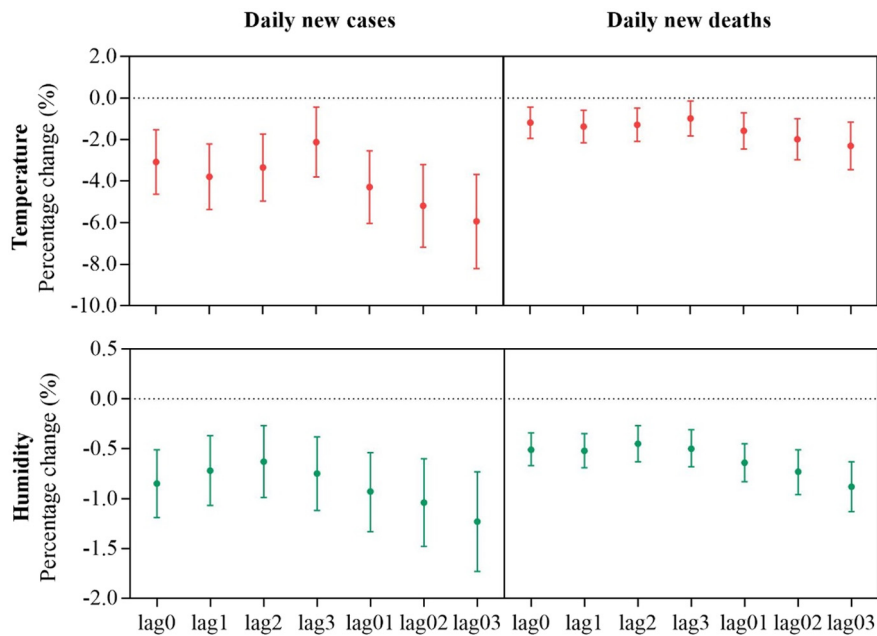


Fig. 2. Effects of temperature and relative humidity on daily new cases and daily new deaths of COVID-19 in different lag structures.

cells, thus exposing the host to the virus (Sun et al., 2020; Lowen et al., 2007). During viral infections, cells release signal proteins to alert neighboring cells of the danger of virus invasion. However, this innate immune defense system is compromised in low-humidity environments (Sun et al., 2020; Kudo et al., 2019). Therefore, the human body is at a higher risk of infection by viruses in low-temperature and low-humidity environments.

Most respiratory viruses exhibit a seasonal trend of infection, such as the influenza virus, SARS-CoV. In 2019, a study by Price et al. (2019) demonstrated that the respiratory syncytial virus and influenza A virus exhibited obvious seasonality, peaking in November–December and December–January, respectively. In 2010, Gaunt et al. (2010) analyzed samples from 11,661 patients with respiratory tract infection from Edinburgh Hospital. This study reported that three types of coronavirus (HCoV-HKU1, HCoV-NL63 and HCoV-OC43) had significant winter seasonality, mainly causing infection between December and April, which is similar to the transmission pattern of influenza (Gaunt et al., 2010). In 2005, Lin et al. (2006) analyzed the potential effect of environmental factors on the SARS epidemic in Hong Kong. The results revealed that temperature was significantly correlated with the spread of SARS after adjustment for several factors, including various interventions, the number of medical staffs infected, the number of patients in intensive care units. The risk of increased daily incidence of SARS in lower temperatures was 18.18-fold (95% CI: 5.6, 8.8) higher than that in higher temperatures (Lin et al., 2006). These studies indicate that SARS-CoV-2 may have a similar seasonal trend to other respiratory viruses, and high temperature may inhibit its spread.

The COVID-19 pandemic is currently displaying an even more adverse trend. The future growth trend of COVID-19 has attracted considerable attention as the northern hemisphere enters summer. Our results suggest that the growth rate of COVID-19 may slow with an increase in

temperature and humidity. However, COVID-19 is in a stage of high infectivity and rapid transmission. The latest study estimated that the basic reproduction number (R_0) of COVID-19 was approximately 5.7 (95% CI: 3.8–8.9) (Steven et al., 2020). Furthermore, confirmed cases of COVID-19 have been reported in the African equatorial and Amazon rainforest regions (Brazilian Health Agency, 2020); therefore, the effect of temperature and humidity on COVID-19 transmission is not sufficient to fully inhibit the pandemic. Countries must take active measures to control the first pandemic and prevent a second wave of COVID-19 (Leung et al., 2020).

The advantages of this study are as follows. First, all countries in which COVID-19 cases had been reported, as of March 27, 2020, were included in our study; thus the results reflect the global COVID-19 situation. Second, this study was a time series analysis, which eliminated the long-term trend of the COVID-19 epidemic, and daily meteorological data were used to accurately reflect the effect of temperature and humidity on the daily new cases and daily new deaths of COVID-19. Third, this study further included variables that reflected economic level, medical conditions, population aging, and population density to reduce confounding bias.

However, several limitations must be considered. First, the dates of reporting from the WHO daily COVID-19 situation reports were used instead of the date of onset in our study, which may engender bias because the time interval varied depending on the medical conditions, policy formulation and diagnostic criteria of each country. Second, the number of confirmed cases was inevitably underestimated, especially in low-income regions, because of the low detection coverage of COVID-19. Third, the effects of policies and measures on COVID-19 transmission were not assessed in our study; however, certain measures, such as quarantine, may affect the prevalence of infectious diseases. Finally, ecological fallacies may have arisen as a result of using

Table 1

Estimated changes with 95% confidence intervals in daily new cases and daily new deaths percentage change (%) associated with each 1 unit increase in temperature and relative humidity, after controlling the HDI and population density.

Variables	Daily new cases				Daily new deaths			
	β	95%CI		P	β	95%CI		P
Temperature ($^{\circ}\text{C}$)	−2.85%	−4.40%	−1.31%	<0.01	−0.65%	−1.40%	0.099%	0.089
Relative humidity (%)	−0.87%	−1.22%	−0.53%	<0.01	−0.46%	−0.63%	−0.29%	<0.01

Table 2
Estimated changes with 95% confidence intervals in daily new cases and daily new deaths percentage change (%) associated with each 1 unit increase in temperature and relative humidity among countries with over 10 days since the first reported case and countries with over 100 cumulative cases.

Countries	Variables	Daily new cases			Daily new deaths				
		β	95%CI	P	β	95%CI	P		
Over 10 days since the first reported case	Temperature (°C)	−3.05%	−4.63%	−1.47%	<0.01	−1.22%	−2.00%	−0.45%	<0.01
	Relative humidity (%)	−0.87%	−1.21%	−0.52%	<0.01	−0.51%	−0.68%	−0.34%	<0.01
Over 100 cumulative cases	Temperature (°C)	−2.82%	−4.60%	−1.03%	<0.01	−1.25%	−2.16%	−0.34%	<0.01
	Relative humidity (%)	−0.86%	−1.25%	−0.47%	<0.01	−0.53%	−0.73%	−0.33%	<0.01

the temperature and humidity of the capitals to reflect the national mean temperature and humidity, and using outdoor exposure as a proxy for personal exposure.

5. Conclusions

These findings provide preliminary evidence that the COVID-19 pandemic may be partially suppressed with temperature and humidity increases. However, active measures must be taken to control the source of infection, block transmission and prevent further spread of COVID-19.

Abbreviations

COVID-19	
Corona Virus Disease 2019	
SARS-CoV-2	
severe acute respiratory syndrome coronavirus 2	
WHO	World Health Organization
GAM	generalized additive model
GHSI	Global Health Security Index
HDI	Human Development Index
CI	confidence intervals

Ethical approval and consent to participate

Not applicable.

Availability of supporting data

The datasets used and/or analyzed during the current study are available from the websites.

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CRediT authorship contribution statement

Yu Wu: Writing - original draft, Methodology, Software, Data curation. **Wenzhan Jing:** Writing - review & editing, Visualization. **Jue Liu:** Writing - review & editing, Supervision, Methodology. **Qiuyue Ma:** Data curation, Methodology, Validation. **Jie Yuan:** Data curation, Investigation. **Yaping Wang:** Data curation, Investigation. **Min Du:** Data curation, Investigation. **Min Liu:** Conceptualization, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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